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VALIDATION OF NOAA/AVHRR AEROSOL RETRIEVALS USING SUN-PHOTOMETER MEASUREMENTS FROM R/V AKADEMIK VERNADSKY IN 1991

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ABSTRACT

NOAA has produced aerosol optical thickness $\tau^A{}_{SAT}$ retrievals from NOAA-11 over oceans operationally since 1990 /1/. The upward radiances L ($W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$) in AVHRR/Channel 1 (Ch1; λ=0.63 μm) are converted to $\tau^A{}_{SAT}$ using a look-up-table (LUT), pre-calculated for various combinations of illumination-observation geometries assuming all oceanic and aerosol optical parameters constant but the total aerosol amount /2/. An earlier paper /3/ described the results of $\tau^A{}_{SAT}$ validation using a set of sun-photometer (SP) measurements $\tau^A{}_{SP}$ from the R/V Akademik Vernadsky during its Cruise in the Atlantic ocean and Mediterranean Sea in Sept-Dec 1989 (AV-89) /4/. That analysis revealed errors in $\tau^A{}_{SAT}$. This paper provides an independent check of that conclusion using the SP measurements taken during another Cruise of the R/V Akademik Vernadsky in Jul-Sept 1991 (AV-91), using the same validation methodology as described in /3/. The results of the two experiments are in agreement.

VALIDATION OF THE OPERATIONAL $\tau^A{}_{SAT}$

Operational algorithm. Aerosol retrievals are made in cloudless pixels, not contaminated by direct sun glint /2,3,5/. In the model /2/, aerosol over ocean is assumed to be non-absorbing (refractive index n=1.5-0.0i) and to obey a modified Junge size distribution dN/dr=0 ($r<r_{min}$ & $r>r_{max}$); A ($r_{min} \le r \le r_m$); $A \cdot (r/r_m)^{-(\nu+1)}$ ($r_m \le r \le r_{max}$). Here r_{min}=0.03; r_m=0.1; r_{max}=10 μm; ν=3.5 (an equivalent Ångstrom exponent $\alpha \approx 1.5$). The Elterman's vertical profile of aerosol concentration A(h); midlatitude ozone profile with integrated content of 0.316 atm·cm; and Lambertian ocean with albedo ρ^S=1.5% are assumed. The specified model establishes a unique relationship between aerosol optical thickness and the upward radiance. This fact underlies the operational algorithm which uses the LUT, precalculated with the radiative transfer code /6/, to retrieve $\tau^A{}_{SAT}$ from the satellite radiances L, corrected for the Sun-Earth distance, and to scale it to λ=0.5 μm, consistently with the retrieval model. Shortly after launch of the NOAA-11 in Sept 1988, it became clear that the pre-launch calibration for Ch1 was inconsistent with the physical algorithm of retrieval. $\tau^A{}_{SAT}$ was underestimated, and it tended to increase with latitude. An attempt was made to correct for both effects simultaneously by adding to the operational albedo α_{op} a term $\Delta\alpha = 2.135 - 0.0288 \cdot \Theta_s$. Θ_s is the solar zenith angle in degrees; albedo $\alpha = 100 \cdot \pi \cdot L \cdot W \cdot F_s^{-1}$. For NOAA-11, the effective solar constant and equivalent width of Ch1 are F_s=184.1 $W \cdot m^{-2}$ and W=0.113 μm, respectively. In case negative retrievals still occur, those are replaced by zeros.

Validation. In order to check the consistency of the described algorithm with the SP and satellite data, we convert L to $\tau^A{}_{SAT}$ using the LUT and compare with $\tau^A{}_{SP}$. Also, we allow negative $\tau^A{}_{SAT}$ retrievals to analyze the physics of the phenomena more clearly. The methodology of validation used here is described in detail in /3/. The accuracy of $\tau^A{}_{SP}$ measured in AV-91 was proven to be ~0.01 in 3 SP channels centered at 0.44, 0.48, and 0.55 μm /7/. $\tau^A{}_{SP}$ was scaled log-linearly to the wavelengths 0.5 and 0.63 μm used in the validation. From ~1000 SP measurements taken during AV-91, the closest in time, within 2-hours of the satellite overpasses, were selected. The ten nearest satellite retrievals, within 300 km of the ship, were selected. The spatial homogeneity and temporal stablity of the aerosol field was analyzed using τ^A_{SAT} and τ^A_{SP}. Totally, 38 reliable matchups (days) were selected after that analysis. They are clustered mostly in two regions of the North Atlantic: 25-35°N, 20-30°W (south of the Azores); and 37-43°N, 60-70°W (Gulf Stream). Averaging of τ^A_{SAT} over the 10 points (after bright outliers, indicating residual cloud, were removed), and τ^A_{SP}, over those closest to the satellite overpass, was applied to suppress noise resulting from natural variability and measurement errors in both data sources. Comparing the averaged characteristics is also consistent with the gridded NOAA operational product which provides an objective analysis of τ^A_{SAT} fields over a $(1°)^2$ x 1 week space/time box /1/. Results of comparison of the τ^A_{SAT} and τ^A_{SP} scaled at 0.5 μm are presented in Fig.1a. Comparison with AV-89 data (table below the figure) shows that the τ^A_{SAT} is underestimated as compared to τ^A_{SP}. We will explore now possible reasons for this systematic error.

Re-calibration. The radiance L in AVHRR solar channels is calculated as $L=(C-C_o)/\gamma$, C being the measured count, γ gain, and C_o offset. The gain is not controlled in flight and drifts in time /8/. The operational recalibration fails to account for that decay. The satellite radiances were re-calibrated using the Pathfinder recommendations. For the period of AV-91 experiment (Jul-Sept 1991), the effective value of gain was $\gamma=1.76\pm0.03$, and offset $C_o=40$. The results of AV-91 and AV-89, after recalibration, still indicate underestimation in τ^A_{SAT} (Fig.1b).

Re-scaling. One possible source of systematic error in τ^A_{SAT} is their scaling from $\lambda=0.63$ μm to 0.5 μm. To remove this atmospheric model dependent error, we carry out all subsequent analyses at $\lambda=0.63$ μm. Eliminating of this scaling results in increasing the systematic difference between the SP and satellite data (Fig.1c). The main conclusion from these analyses is that the physical model of retrieval is inconsistent with the satellite and SP data in both experiments. This manifests itself in both a pronounced negative bias $(\tau^A_{SAT}-\tau^A_{SP})<0$ and a slope of the regression line $(d\tau^A_{SAT}/d\tau^A_{SP})<1$.

PHYSICAL ANALYSIS OF THE ERRORS

The linearized single scattering approximation of the radiative transfer equation /9,10/ gives the following equation for τ^A retrieval, which is convenient for qualitative analysis of the errors:

$$\tau^A_{SAT}=(\rho-\rho^M-\rho^S\cdot T)\cdot(4\cdot\mu_v\cdot\mu_s)\cdot(\omega\cdot P^A)^{-1} \qquad (1)$$

where $\rho=\pi\cdot L\cdot W\cdot F_s^{-1}\mu_s^{-1}$; ρ^M is the Rayleigh scattering contrubution to the total signal ρ; ρ^S is the diffuse surface reflectance; T is the total atmospheric transmittance; P^A and ω are the generalized aerosol phase function (which includes the effect of diffuse sky light Fresnel' reflection) and albedo of single scattering; $\mu_v=\cos\Theta_v$; $\mu_s=\cos\Theta_s$; Θ_v and Θ_s are the view and solar zenith angles. From (1) it follows that the errors in τ^A_{SAT} may result from incorrect ρ^S, ω, or P^A since the terms of ρ^M and T are well known. Note that ρ^S participates in Eqn.(1) as an additive term, and $(\omega\cdot P^A)$ as a multiplicative one. This suggests that the negative bias in the satellite retrievals comes from overestimating the oceanic reflectance, and the depressed slope $(d\tau^A_{SAT}/d\tau^A_{SP}<1)$ from an incorrect aerosol model (ω and/or P^A).

OCEANIC REFLECTANCE

The oceanic model used in the operational algorithm overestimates the diffuse component ρ^S for typical oceanic conditions, and disregards the effect of Fresnel reflection of diffuse sky radiation by the surface -- diffuse glint /3,9,10/. The diffuse component of surface reflectance, ρ^S, for Ch1 spectral range (0.58-0.68 μm) is typically $\rho^S=0.2\%$ over deep ocean waters /9/ rather than 1.5% used in the operational algorithm. The effect of replacing the diffuse reflectance and including diffuse glint (reflection from a flat sea surface using the single scattering approxomation /9,10/) on the τ^A_{SAT} retrieval is presented in Fig.1d. The negative bias in both data sets is removed. The slopes of the regression lines are lowered further. This result may be explained only by errors in the aerosol model, i.e. an incorrect $(\omega\cdot P^A)$ product being used in the operational retrieval. The increased correlation suggests that a new aerosol model may be able greatly reduce this systematic error for both sets of experimental data. Following /3/, we demonstrate here that a simple adjustment to the operational model can reconcile the satellite and SP data in both data sets.

AEROSOL MODEL

Incorrect P^A or ω result from an incorrect aerosol model used in the retrieval algorithm. The aerosol model being used assumes spherical particles, and a modified Junge size distribution with fixed parameters of r_{min}, r_m, r_{max}, ν, and refractive index. The spectral dependence of aerosol optical thickness in the case of Junge's size distribution obeys the Ångstrom's law $\tau(\lambda) \sim \lambda^{-\alpha}$, $\alpha \approx (\nu-2)$ being Ångstrom's exponent. An effective α estimated from the SP data by means of regression of $\tau^A_{SP}(\lambda=0.48\ \mu m)$ vs $\tau^A_{SP}(\lambda=0.55\ \mu m)$ gives, on the average, $\alpha \approx 0.66$ for 1000 SP measurements during the AV-91 (the latter result is consistent with AV-89 data), which suggests that the mean effective value of the Junge' exponent is $\nu \approx 2.5$, rather than 3.5 used in the model. The effect of replacing this parameter is shown in Fig.1e. This results in a decrease of the slope and deterioration of the regression analysis which implies inconsistency of the assumed retrieval model (spherical particles with the modified Junge' size distribution) with the scattering properties of the atmosphere. The latter conclusion means that a fundamental revision of the aerosol microphysical model is required which is underway now. For the present, we follow /3/ and try the effect of increasing the imaginary part of the aerosol's index of refraction (Fig.1f). Substituting Im(n)=0.01, one obtains, to a good approximation, agreement between SP and satellite data in both cases. To be certain about the correct aerosol microphysics, the aerosol physical and chemical properties should be measured at each match-up point. This is the goal of the field program being planned for the summer of 1995, off the east coast of the U.S. /11/.

CONCLUSION

Analysis of the two match-up data sets reveals errors in the operational NOAA/NESDIS τ^A_{SAT} retrievals. After re-calibration of the satellite data and correction of the oceanic reflectance model, the remaining multiplicative underestimation in τ^A_{SAT} indicates, on the one hand, the necessity for an atmospheric model revision. On the other hand, its systematic character is encouraging, in that a simple adjustment to the currently used aerosol model will, to a first approximation, bring the SP and satellite data into agreement. An example of such an adjustment in the aerosol absorption is given. Further investigations are needed, together with intensive field measurements, to establish a more appropriate aerosol model.

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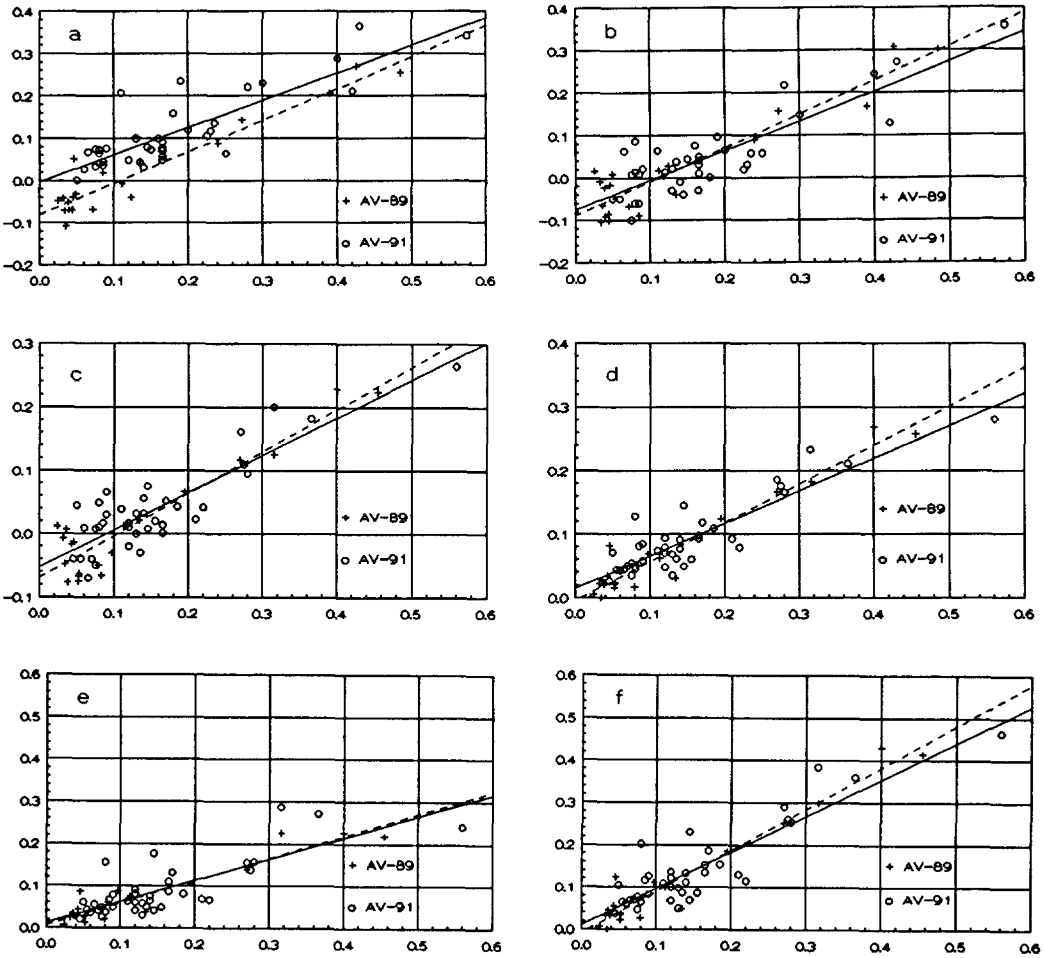

Fig.1. Scattergrams of τ^A_{SAT} (Y-axis) versus τ^A_{SP} (X-axis) for AV-91 (N=38) and AV-89 (N=20). Linear regression lines are shown for AV-91 (solid) and AV-89 (dashed). Standard deviations of the regression coefficients are included in the table of coefficients below.

a. operational (λ=0.5 μm).
AV-91 τ^A_{SAT}=(-.004±.014)+(.65±.07)·τ^A_{SP} σ=.047 R^2=.72
AV-89 τ^A_{SAT}=(-.081±.011)+(.75±.06)·τ^A_{SP} σ=.036 R^2=.91

b. τ^A_{SAT} from recalibrated radiances (λ=0.5 μm).
AV-91 τ^A_{SAT}=(-.076±.015)+(.70±.07)·τ^A_{SP} σ=.050 R^2=.73
AV-89 τ^A_{SAT}=(-.089±.015)+(.80±.07)·τ^A_{SP} σ=.047 R^2=.87

c. the same as in b) but for λ=0.63 μm.
AV-91 τ^A_{SAT}=(-.054±.011)+(.59±.06)·τ^A_{SP} σ=.036 R^2=.75
AV-89 τ^A_{SAT}=(-.070±.011)+(.66±.06)·τ^A_{SP} σ=.034 R^2=.87

d. the same as c) but oceanic reflectance corrected.
AV-91 τ^A_{SAT}=(.015±.008)+(.51±.04)·τ^A_{SP} σ=.027 R^2=.79
AV-89 τ^A_{SAT}=(-.004±.007)+(.61±.04)·τ^A_{SP} σ=.022 R^2=.93

e. the same as d) but ν=2.5 instead of 3.5.
AV-91 τ^A_{SAT}=(.011±.012)+(.51±.07)·τ^A_{SP} σ=.041 R^2=.63
AV-89 τ^A_{SAT}=(.007±.008)+(.53±.04)·τ^A_{SP} σ=.025 R^2=.89

f. the same as e) but Im(n)=0.010 ($\omega\approx$0.9 for $\nu\approx$2.5).
AV-91 τ^A_{SAT}=(.011±.014)+(.86±.07)·τ^A_{SP} σ=.046 R^2=.79
AV-89 τ^A_{SAT}=(-.008±.011)+(.98±.06)·τ^A_{SP} σ=.033 R^2=.94